#12 Declaration
Smw 5-20-03

Docket No. 12-0895

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of:

David L. Rollins

Serial No.: 09/322,283

Filed: May 28, 1999

For: LINEARIZED OPTICAL LINK USING A SINGLE MACH-ZEHNDER MODULATOR AND TWO OPTICAL CARRIERS

Group Art Unit: 2633

Examiner: Sedighian, Reza

"Certificate of Mailing"

I hereby certify that this paper is being deposited with the United States Postal Service with sufficient postage as first class mail in an envelope addressed to: Commissioner of Patents and Trademarks, Washington, D.C. 20231 on this date:

4-30-03 John S. Paniaguas
Date John S. Paniaguas
Registration No. 31,051

Declaration of David L. Rollins under 37 CFR 1.131

Commissioner for Patents
Washington, D.C. 20231

Dear Sir:

I, David L. Rollins, pursuant to 37 C.F.R. §1.131, declare as follows:

1. I am the sole inventor of the invention in the above-identified patent application.

2. I conceived the invention set forth in the above-identified application while employed at TRW Inc., prior to April 21, 1998, the filing date of Burns U.S. Patent No. 5,917,970, which is prior to the filing dates of Dishman et al. U.S. Patent No. 6,271,953 and Franck et al. U.S. Patent No. 6,188,497; which is also prior to the article entitled, "Linearization of a Broadband Analog Optical Link Using Multiple Wavelengths" by Edward Acherman, Technical Digest

International Topical Meetings on Microwave Photonics, October 12-14, 1998, Sarnoff Corporation, Princeton, New Jersey, pages 45-47.

3. Attached is a copy of my invention disclosure for this case dated February 23, 1998. Also attached is a copy of an internal TRW presentation dated March 5, 1998. Both of these documents clearly indicate that the invention was conceived and reduced to practice well before the date of any of the cited references.

FURTHER DECLARANT SAYETH NOT

Date: 4/30/2003

David L. Rollins

TRW PROPRIETARY
INVENTION DISCLOSURE

TRW

See Instructions on Last Page of This Form

MAR 0 2 1998

Docket No. 12-0595

Date 2/23/98

Title of Invention: Linearized Optical Link Using a Single Mach-Zehnder Modulator and Two Lasers

310-812-9409

Inventor(S)

Full Name (No Initials)	Badge No.	Division	CCC	TRW Mail Station	Extension	Immediate Supervisor
David Lawrence Rollins	104309	ES&TD	D605	O3/1270A	x29409	Rick Fields

Conception of Invention

Date of First Written Description of the Invention 12/19/97

In Engineering Notebook? Yes ☒ Notebook No 28951 Page 1-3

No ☐ If No, Identify the Written Description and Indicate Where Located

Date of the First Oral Disclosure 12/17/97 To Whom? Rick Fields, James Leight

Date of First Drawings or Sketches 12/19/97 Present Location Eng Notebk

Construction And Test

Invention Constructed Or Modeled Yes ☒ No ☐ Date 2/98

By Whom? Modeled by David Rollins

Invention Successfully Tested? Yes ☐ No ☒ Date

By Whom?

Names of Witnesses to the Construction or Testing

Were Formal Drawings Made Yes ☐ No ☒ If Yes, Drawing Nos.

Use

Was Invention the Subject of Commercial Activity? Yes ☐ No ☒
(Commercial Activity Means External to TRW and Includes Activity with the Government)

If Yes (A) Date of First Executed Sales Contract

(B) Identify First Sale Contract No.

(C) Date Of First Delivery To Customer

Date of First Commercial Activity, Either with Commercial Customers or in a Proposal to Government

Is Commercial Activity Imminent? Yes ☐ No ☒ Expected Date

SYSTEMS125 Rev. 09-93

Publication

Has a Description of the Invention Been Published? Yes ☐ No ☒

If Yes, Provide Copy and Identify Publication and Date

If The Invention Has Been Described in a Customer Report Provide Copy And Identify the Customer Report by Customer, Date, and No.

Did the Customer Report Have a TRW Proprietary Legend? Yes ☐ No ☐

Has the Invention Been Described to People Not Employed by TRW? Yes ☐ No ☒

If Yes (A) Was Disclosure Under a Confidential Disclosure Agreement

(B) Provide Names of Person(S), Their Employers(S), Date, and Place of Disclosure

Related Printed Publications and Reference Material

Identify Any Patents, Printed Publications, Written Reports, or Proposals Relating to Closely Analogous Concepts, and Provide Copies

Identify Any Prior TRW Invention Disclosures, Patent Applications, or Issued Patents Relating to the Invention

Similar to SOBS concept (TRW Patent Application, Docket No. 11-0844) since multiple wavelengths are simultaneously modulated with 1 modulator. Also uses a balanced photodetector. Also · 12-0704

Contract or Project Information (Must Be Completed)

The Invention First Conceived While Charging Time to Job No. 98JYWH And Working on:

☐ Government Contract or Subcontract No. ______ Title ______

☒ TRW Funded (IR&D, B&P, PM&P) Project No. IR&D Title Target Adv Antenna Array

☐ Commercial Contract No. ______ Customer ______

☐ Other, Explanation ______

Contract Administrator ______

The Invention First Conceived While Charging Time to Job No. ______ And Working On:

☐ Government Contract or Subcontract No. ______ Title ______

☐ TRW Funded (IR&D, B&P, PM&P) Project No. ______ Title ______

☐ Commercial Contract No. ______ Customer ______

☐ Other, Explanation ______

Contract Administrator ______

[signature] 2-27-98

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Problem or Need

Most analog optical links suffer from at least one of three disadvantages: poor sensitivity, low dynamic range or low RF bandwidth. Linearized direct modulated lasers generally have high dynamic range, but poor sensitivity and limited bandwidth. Standard external modulators are wideband and have better sensitivity, but poor dynamic range. Most linearization schemes for external modulators improve dynamic range at the expense of sensitivity. The current invention improves dynamic range and sensitivity.

Inventive Concept (What It Does and How It Does It)?

The inventive concept is to low-bias a standard Mach-Zehnder modulator for sensitivity improvement, but at the same time use two optical wavelengths with two effective bias points to cancel the even-order distortion associated with low-biasing. The two wavelengths are chosen to simultaneously bias the modulator at two bias points on opposite sides of the minimum bias point. Thus they will have equal gains with opposite signs (one inverting and the other non-inverting). The demodulator contains a WDM to separate the two wavelengths, two separate photodetectors to detect the two wavelengths and a circuit to subtract the two photodetector currents. The currect subtraction circuit sums the fundamental signals coherently, since their gains had opposite signs, and cancels the even order distortion, since they have the same amplitude sign. This pair of photodetectors and current subtraction circuit is called a balanced photodetector which is often used to cancel RIN noise.

whats new?

Prior Art See attached block diagrams of Mach-Zehnder based optical links.

Inventor [signature]	Date 2-27-98	Inventor	Date	Inventor	Date
Witnessed, Read and Understood by:	[signature] Witness	2-27-98 Date	Witnessed, Read and Understood by:	[signature] Supervisor	2/27/98 Date

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Advantages

The current invention mitigates the main disadvantage of low-biasing a Mach-Zehnder modulator without sacrificing its advantages: It improves the 2nd-order SFDR without degrading 3rd-order SFDR or sensitivity. It can actually improve the sensitivity by using two lasers and two photodetectors. It also makes the modulator bias control circuitry simpler. Since the two lasers need to be biased symmetrically about a minimum bias point, a copy of the receiver's demodulator is coupled to the MZM output and DC bias voltage is adjusted to null differential DC photocurrent . No dither is needed.

Government, Industrial or Commercial Applications

The current invention can be used in applications requiring an analog photonic link with high sensitivity and high dynamic range with a significant amount of loss between the modulator and the demodulator. An example is analog signal remoting from an antenna to a processing site with fiber optic cable lengths of 10 to 100 kilometers. Another application would be an analog crosslink between two satellites.

Illustrations and/or Examples (Attach Drawings) Figure 1 shows how the bias point of a Mach-Zehnder modulator is different for different wavelengths for the same effective path length difference (i.e. bias voltage). Figure 2 shows block diagrams of a basic optical link and a balanced detector optical link and the proposed linearized optical link. This link architecture will be presented at the internal TRW Signal Processing conference (copy attached).

Inventors Names, Social Security Nos., Home Addresses and Telephone Numbers

1. David Lawrence Rollins, 419-04-5068, 15000 Gerkin Ave, Hawthorne, CA 90250, (310) 675-5085

2.

3.

4.

Inventor	Date	Inventor	Date	Inventor	Date
[illegible]	2-27-98				

Witnessed, Read and Understood by:	[illegible]	2-27-98	Witnessed, Read and Understood by:	[illegible]	2/27/98
	Witness	Date		Supervisor	Date

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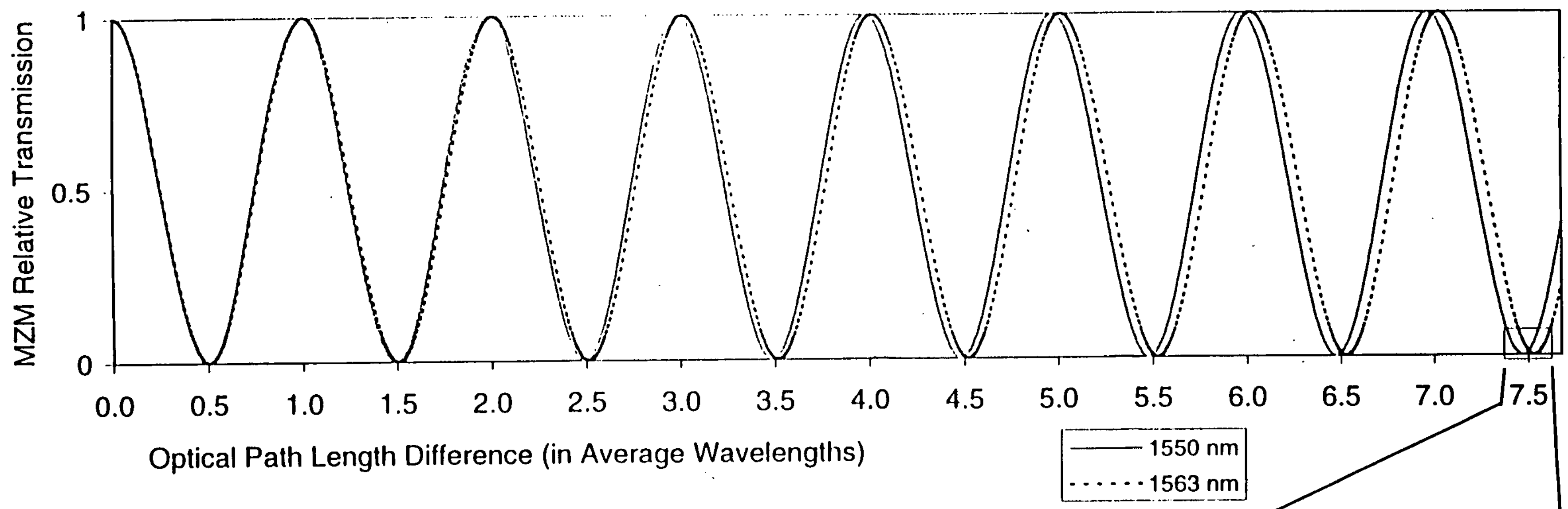

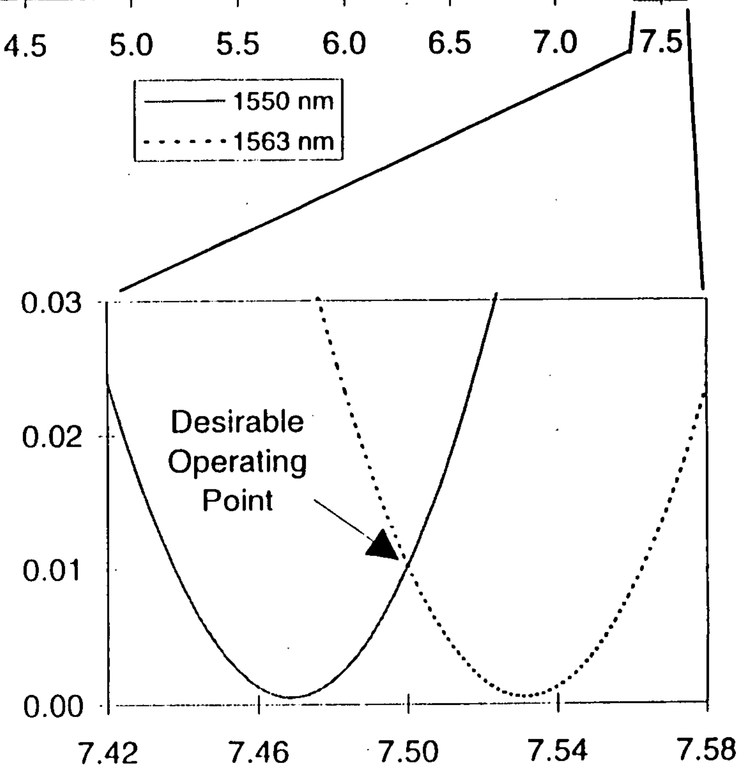

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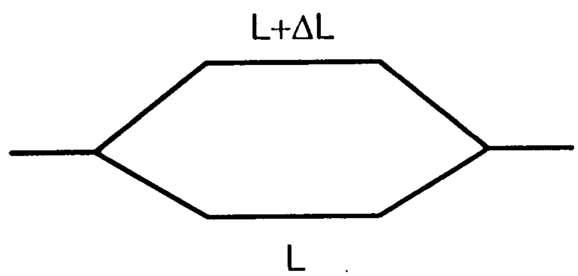
Mach-Zehnder Modulator



Optical path length difference is set by a combination of physical path lengths and effective path length changes due to applied voltages (bias voltage plus small signal voltage) which change the index of refraction of the waveguides

Figure 1 Wavelength Effects on Mach-Zehnder Modulator Bias Points

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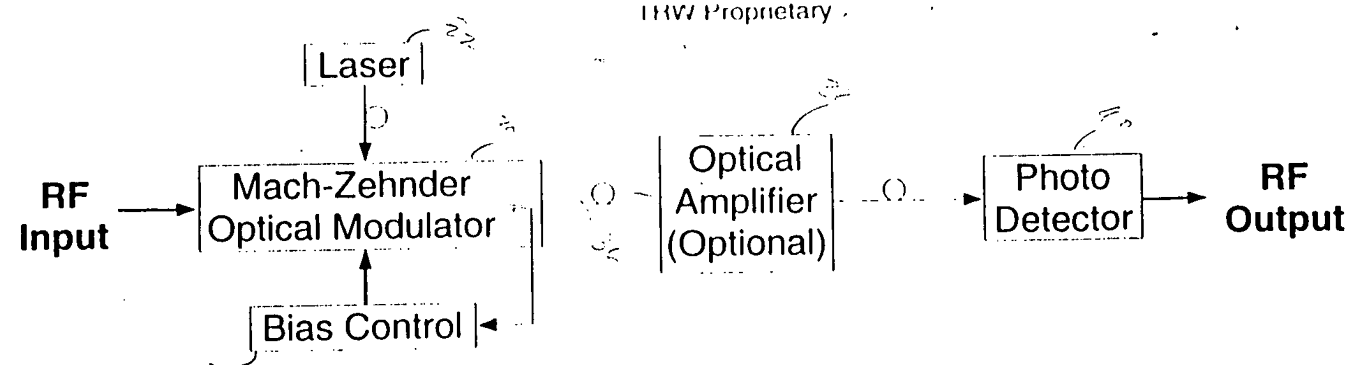
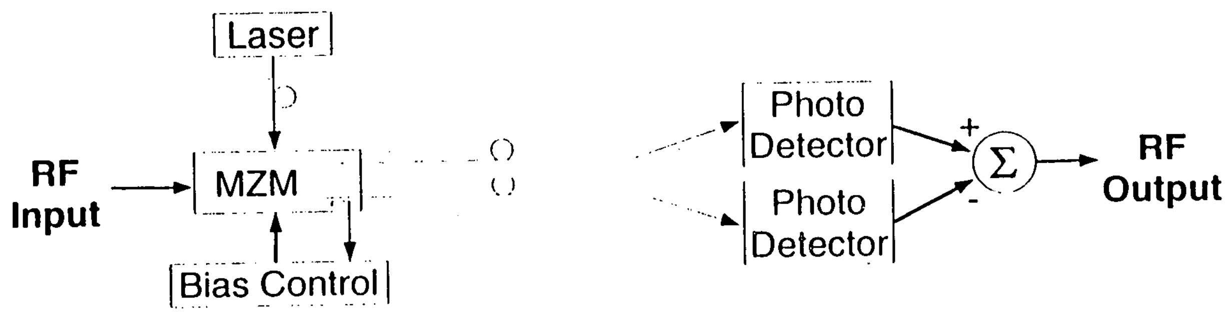


(a) Basic Mach-Zehnder Optical Link

3



(b) Balanced Mach-Zehnder Optical Link

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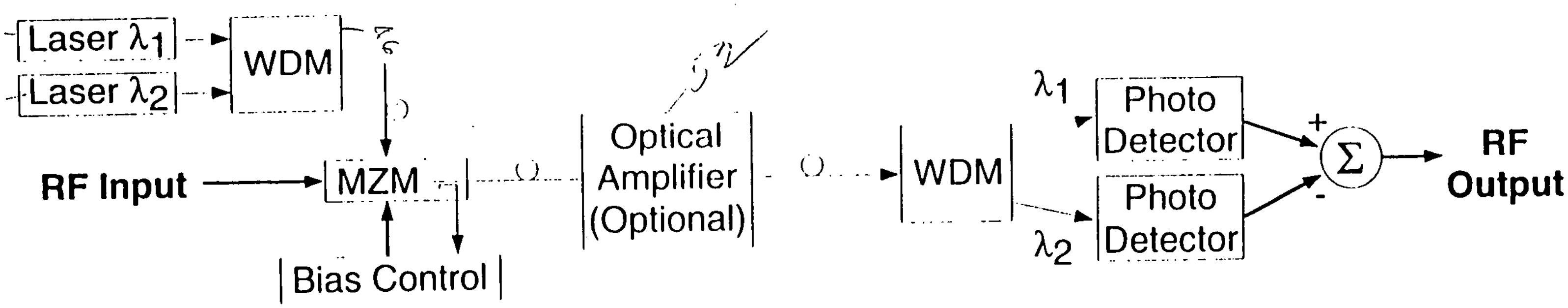

(c) Two Wavelength Linearized Mach-Zehnder Optical Link

Figure 2 Optical Link Block Diagrams

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Linearized Optical Link with Improved Sensitivity

Using One Mach-Zehnder Modulator and Two Lasers with Different Wavelengths

David Rollins
O3/1270A x29409
March 5, 1998

An invention disclosure for this concept has been submitted to the TRW patent board.

TRW Proprietary

Need for Externally Modulated Analog Optical Links with Improved Spur Free Dynamic Range and Sensitivity

- Sacrificing sensitivity to improve spur free dynamic range not a good trade
  - Most linearization schemes for externally-modulated links significantly degrade link sensitivity to improve spur free dynamic range (SFDR)
  - Analog optical links generally have poor sensitivity to begin with
  - Degrading sensitivity increases the RF drive amplifier gain and linearity requirements to the point where the RF amp limits the overall SFDR, significantly reducing the benefit of the linearization scheme
  - Direct-modulated lasers are often linearized, but have very poor sensitivity
- Improved link SFDR needed to minimize transmitter output optical power in lossy links
  - SFDR is a function of Rx power when sensitivity set by Rx optical preamplifier
  - Standard links using quadrature-biased Mach-Zehnder Modulators (MZMs) are far from optimal in terms of third-order SFDR
  - An ideal (linear) intensity modulated link can give 3rd-order SFDR 30dB better than a quadrature-biased MZM link

TRW Proprietary

Sensitivity of links based on standard quadrature-biased Mach-Zehnder modulators can be improved by either lowering the switching voltage (Vpi), which is a basic device research problem, and/or by using higher power optical amplifiers in the transmitter to get more optical power at the receiver's optical preamplifier input. Note that care must be taken to prevent other noise sources from degrading the sensitivity set by this optical preamp, such as laser RIN noise, shot noise and transmitter optical amplifier noise.

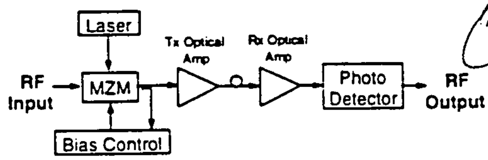
Another way to improve the link's sensitivity is to low-bias the modulator, which gives it a better relative gain as measured by the slope of its transfer function normalized by its transmission at the bias point.

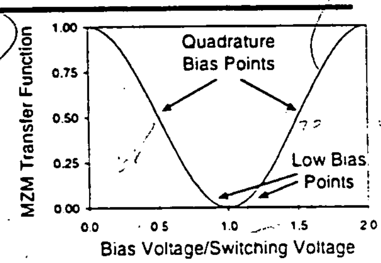
Most linearization schemes for Mach-Zehnder modulator-based links require at least two modulators and unequal power splitting of the RF signal between the modulators. The degree of linearization is highly dependent on the accuracy of these splitting ratios. The SFDR is improved at the expense of sensitivity (which increases the linearity requirements on the RF amp driving the MZM).

This presentation will discuss an alternative approach that uses two equal-power lasers (with different wavelengths) to simultaneously modulate the RF signal using only one modulator. This new method requires no RF power splitting and performs well with modest laser power matching and simple ditherless control loops.

TRW Proprietary

Basic Mach-Zehnder Analog Optical Link





- Mach-Zehnder modulator (MZM) voltage-to-optical-power transfer function is a raised cosine
  - Quadrature-bias point is the standard, with very good even-order SFDR
    - Bias is preset or controled by nulling 2nd harmonic of a low frequency dither
  - Low biasing improves odd-order SFDR, and sensitivity, but degrades even-order SFDR
    - Bias control is difficult, too sensitive to preset and hard to create active error signal
- Fiber amplifiers and photodetectors are generally assumed to be much more linear than modulators
  - More difficult to analyze, but should be considered when modulators are linearized

TRW Proprietary

Mach-Zehnder modulators can actually be purchased pre-biased at quadrature. This means that no bias voltage or bias control is required. Bias control is only needed when very little even-order distortion can be tolerated. In this case, the dither-based bias control can be used to more accurately set the bias at quadrature.

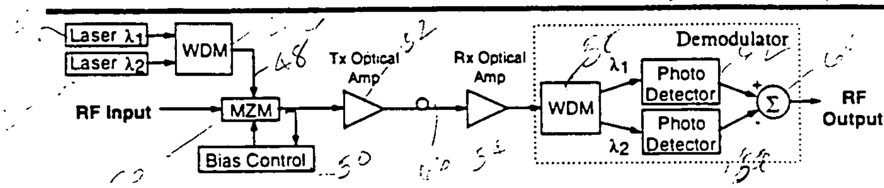
Low-bias is a very vague term since it is really a range between quadrature bias and min bias. Low-bias control is difficult because there is nothing simple to null. The lower the bias the higher the ratio of the fundamental to the third harmonic, but you can only go so far until the low MZM transmission (output power) starts to degrade the sensitivity. A not-so-simple approach to bias control is to inject two phase-locked dithers, say 1 kHz and 2 kHz with carefully chosen amplitude and then null the 2 kHz tone at the MZM output using a coupled photodetector and a lock-in amplifier.

Fiber amplifiers have higher output power levels, lower noise levels and much less distortion than semiconductor optical amplifiers. Thus, fiber amplifiers are preferred for high-dynamic-range links, even though they consume more DC power.

The photodetector converts optical power into electrical current. Most photodetectors used for analog links are really reverse biased (photo) diodes and thus are not completely linear.

TRW Proprietary

Components of Dual Wavelength Low-Biasing Optical Link



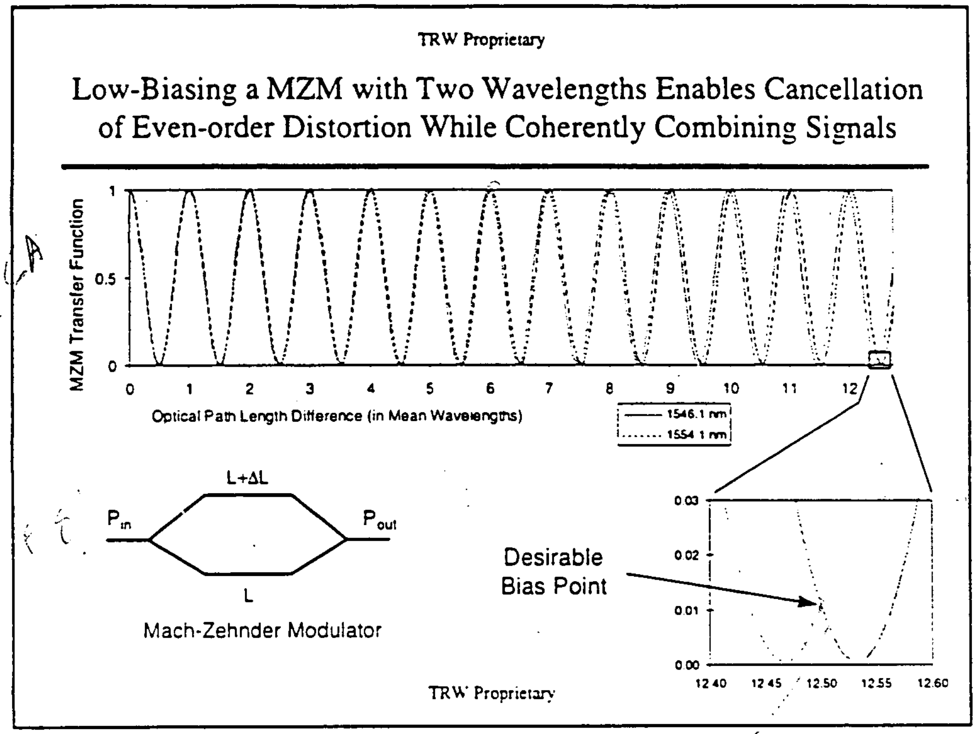
- Two equal-power lasers with different wavelengths are combined onto a single fiber with a wavelength division multiplexer (WDM)
- Combined wavelengths are modulated with RF signal in MZM low-biased such that two wavelengths have complementary small-signal gains
- Optical signal is amplified and transmitted over fiber or free space link
- Received signal is optically amplified and the two wavelengths are demultiplexed with another WDM
- Each wavelength is photodetected separately and the complementary photo-currents are subtracted with a balanced photodetector pair to give the linearized RF output

TRW Proprietary

The bias control in this case can be very simple. The bias control circuit includes of a very low speed copy of the demodulator, and the bias voltage is adjusted to null the differential DC photocurrent. No dither is required. The optical losses (from the laser sources to the bias control's photodetector outputs) are calibrated and then the individual lasers control their own output power.

Optical gain variations in the optical amplifiers and the channel are automatically compensated for in the demodulator, which adjusts the relative photocurrents to null the differential DC photocurrent.

For very high performance links requiring even better even-order linearity, active bias control can be used by injecting a low frequency dither into the MZM with the DC bias voltage. The receiver adjusts the relative photocurrents into the current summer in order to null the dither's second harmonic with a lock-in amplifier. The receiver must also detect the dither fundamental in order to form the reference for nulling this second harmonic. This is very similar to quadrature-bias control, except that the nulling circuit is in the receiver not the transmitter.



A Mach-Zehnder modulator works on the principle of coherent interference. The optical input power is equally split into two optical waveguides (arms). The relative path lengths of these two arms can be changed. When the path lengths are equal or differ by a multiple of the optical wavelength, they add coherently in the output combiner. This gives maximum optical transmission. When the path lengths differ by a multiple of the optical wavelength plus a half wavelength. they coherently cancel in the output combiner (or nearly cancel). This gives minimum optical transmission. At other points, they partially cancel. This interference effect gives the raised cosine transfer function.

The optical path length difference is set by a combination of physical path lengths and effective path length changes due to applied voltages (bias voltage plus small-signal voltage) which change the index of refraction of the waveguides. Note that this concept relies on the linear relationship between the switching voltage (Vpi) and the optical wavelength.

For a roughly fixed optical path length difference, the degree of low-biasing can be (continuously) adjusted by increasing or decreasing the wavelength separation of the lasers. The bias control loop will lock onto the bias point where both wavelengths have equal output power and opposite slope (sign of gain). Alternatively, for a given wavelength separation, the degree of low-biasing can be adjusted in steps by changing the rough optical path length difference in steps of approximately one average wavelength.

Benefits of Dual Wavelength Low-Biased Approach

- Overcomes big drawback of single wavelength low-bias link: even-order distortion
  - MZM even-order distortion cancelled in balanced photodetector while signals add
  - Photodiode even-order distortion also cancelled
- Retains benefits of single wavelength low-bias approach for lossy links
  - Improved sensitivity and increased odd-order SFDR
- Simple, stable low-bias control
  - Bias point set by path length difference and wavelength separation of lasers
  - Bias controlled by nulling differential DC photocurrent in demodulator coupled to MZM output, no dither required

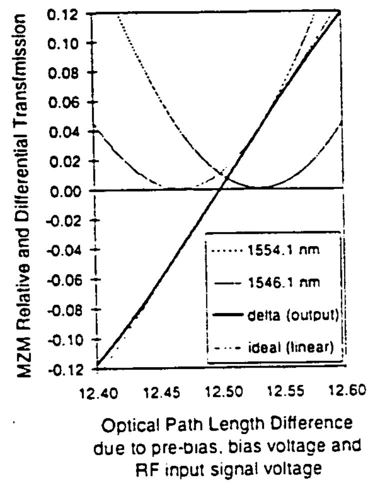


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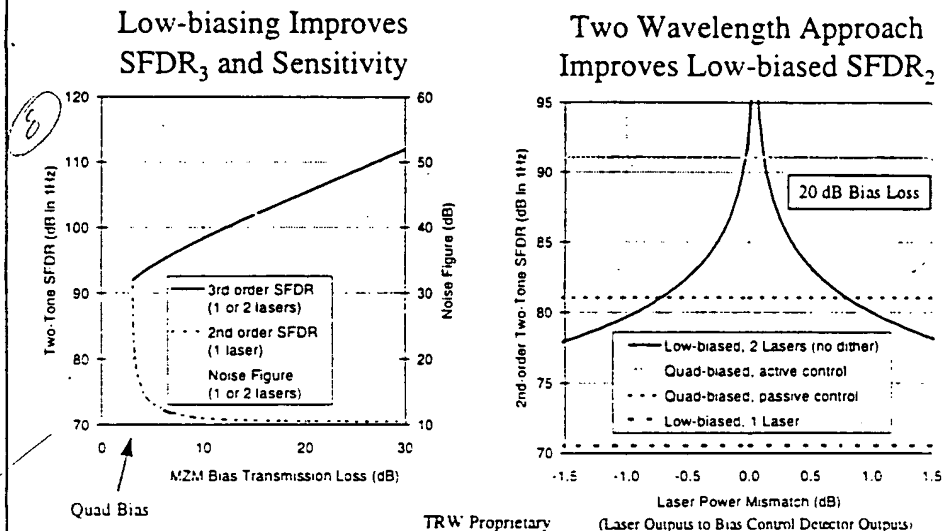
Fig 7

Note that the small-signal voltage can swing the MZM transfer functions way past the minimum bias points before the linearity is significantly degraded. And even here the nonlinearity is mainly third-order.

The degree of cancellation of the even-order distortion is a function of the relative matching of the optical power of the two wavelengths and their losses to the transmitter's coupled balanced detector. Because the two wavelengths have slightly different switching voltages (and thus link gains), the optimal laser power ratio to null even-order distortion is not exactly one. This is why the peak 2nd-order SFDR on the next chart is not at 0 dB laser power mismatch. This optimal mismatch from 0 dB is usually smaller than the calibration accuracy.

TRW Proprietary

Performance Comparisons of Single and Dual Wavelength MZM-Based Optical Links



TRW Proprietary

These plots are based on a lossy link where the noise figure of the receiver's optical preamplifier dominates all other noise sources. Even with a single wavelength, the lower the biasing, the better the sensitivity and 3rd-order SFDR. Also note that the single-wavelength 2nd-order SFDR flattens out for biasing losses above 10 dB.

A ditherless dual-wavelength low-biased link with laser power mismatch (from laser outputs to bias control detector outputs) of less than 0.75 dB has better 2nd-order SFDR than a ditherless quadrature-biased link. A dithered dual wavelength low-biased link should give better 2nd-order SFDR than a dithered (actively controled) quadrature-biased link.

The link parameters used for the curves above are

Nominal wavelength = 1550 nm

MZM switching voltage = 4 volts

MZM input impedance = 50 ohms

Total optical power at Rx input = -20 dBm

Rx optical amp NF = 4 dB

Quadrature-bias 2nd-order SFDR bias accuracy:

2.5 degrees, preset (no control) or 0.25 degrees, with dither

Dual-wavelength 2nd-order SFDR:

MZM path imbalance = 19.375 microns (~ 12.5 wavelengths)

Wavelength spacing = 8 nm

Limitations of Dual Wavelength Approach

- Does not significantly improve gain-compression-type dynamic range when used in link with an optical amplifier in compression
  - Even-order distortion is corrected in the demodulator (receiver), not in the modulator (transmitter)
  - Transmitter optical power amplifier can compress on large even-order distortion in each optical wavelength
- High optical biasing loss in modulator makes it undesirable for short links with few losses
  - Quadrature biasing with high-power laser and no optical amplification gives best performance for low-loss links
- Use of two wavelengths reduces ability to WDM multiple signals on a fiber
  - Also long fiber runs can introduce wavelength dependent dispersion and relative time delays between wavelengths, which must be compensated for before combining the signals from each wavelength

Applications for Dual Wavelength Linearized Optical Link

- Lossy analog optical links requiring good 2nd and 3rd order SFDR and sensitivity
  - When transmitter optical power amplifier is a design driver
  - When receiver optical preamplifier sets the noise floor
- WDM links where only one wavelength per signal is available, but where 2nd-order SFDR is not important
  - In this case, the second wavelength is used for bias control only and is filtered off before combining with other signal wavelengths
- Low-loss links where a lot more optical power is available at the modulator output than the photodetector can handle